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INTEGRATED RECEIVER FOR NASA TRACKING AND DATA RELAY SATELLITE SYSTEM

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ABSTRACT

The Tracking and Data Relay Satellite System (TDRSS) is an integral part of the National Aeronautics and Space Administration (NASA) Space Network. This network provides tracking, telemetry, and command (TT&C) for low earth-orbiting satellites such as the Space Shuttle, Landsat, and the Hubble Space Telescope. In the future, TDRSS will provide the space/ground communications for the Space Station Freedom.

This paper discusses the requirements and design of the Integrated Receiver (IR), an unbalanced quadriphase shift keying (UQPSK) receiver/demodulator under development for use in the TDRSS. The paper presents the top level architecture of the IR and describes the implementation of the primary functions in the receiver.

INTRODUCTION

Transmission of digital data and voice between the myriad of U.S. and allied spacecraft and the associated earth-based Operation Centers (OCs) is accomplished by the NASA developed and operated Space Network, specifically the TDRSS. The TDRSS portion of the Space Network was developed in the late 1970s and became operational in the mid-1980s. Three satellites are currently on orbit, with additional satellites planned for launch in the 1990s.

A Second TDRSS Ground Terminal (STGT) is now under construction at Bear Creek on the NASA White Sands Test Facility (WSTF) in New Mexico. In completing the STGT and retrofitting the existing White Sands Ground Terminal (WSGT), NASA will receive the benefit of more than 10 years of technology advancement since WSGT was developed. These advancements have enabled designers to combine signal processing functions into fewer chassis with more ambitious performance and configuration capabilities. One such chassis is the Integrated Receiver.

The Integrated Receiver performs carrier recovery, data demodulation, PN despreading, and data processing for telemetry data rates for 100 bps to 300 Kbps for spread modes and 1 Kbps to 12 Mbps for nonspread modes. To support coherent demodulation of the TDRS single-access antenna autotrack error signals, the unit's carrier acquisition and track capability extends to the full TDRSS 300-Mbps service limit. In conjunction with its companion ground based modulator, the IR also performs two-way range, both one- and two-way doppler, and time transfer measurements. The original system employed three different demodulator sets (I and Q pairs), plus external symbol synchronizers, decoders, deinterleavers, and data format converters. In all, a single IR replaces the 12 different chassis today required to support a single S-band single-access service.

TDRSS OPERATIONAL COMMUNICATIONS REQUIREMENTS

The TDRSS mission provides a centralized space communications system for low-earth orbiting spacecraft, without the need for an extensive worldwide network of ground terminals. The system must be capable of operating with many varied users through one of three services that are categorized based on the user link frequency and data rate. Table 1 lists the services, modes, and data rates on TDRSS, and indicates whether the service is spread or nonspread and whether the mode includes coherent turnaround at the user transponder. To achieve its operational goals efficiently, the space and ground segments of TDRSS must be reconfigurable in a minimum amount of time to maximize the on-line communication support available.

Table 1. Data Services and Rates on TDRSS

Service		Mode	Data Rate[1]		Spread	Coh
SSA	DG-1	1	I&Q	0.1K-150K	Yes	Yes
		2	I&Q	0.1K-150K	Yes	No
		3	I	0.1K-150K	Yes	Yes
	DG-2	1	I&Q	1K-3M	No	Yes
		2	I&Q	1K-3M	No	Yes
KSA	DG-1	1	I&Q	0.1K-150K	Yes	Yes
		2	I&Q	0.1K-150K	Yes	No
		3	I	0.1K-150K	Yes	Yes
			Q	1K-3M	No	Yes
	DG-2	1	I&Q	1K-150M[2]	No	Yes
		2	I&Q	1K-150M[2]	No	No
MA	DG-1	1	I&Q	0.1K-50K	Yes	Yes
		2	I&Q	0.1K-50K	Yes	No

1 Data rates are continuous ranges in sample per second
2 IR data rates limited to 6 Msps each I&Q

As depicted in Figure 1, each ground terminal supports two TDRS, one "Easterly" and one "Westerly," via K_u band links between the TDRS and one of the main parabolic antennas at the ground terminal. The TDRSS signals sent from the ground to the user spacecraft are referred to as "forward" signals and signals coming from the user spacecraft to the ground are "return" signals, a terminology that sidesteps the confusion that can result from the terms "uplink" and "downlink." In addition to the user communications signals, the TDRSS spacecraft tracking, telemetry and control (TT&C) link is sent between the ground and the TDRS via this path. Being in geostationary orbit, the TDRS provides continuous coverage of a spacecraft in orbit across a full-earth disk, reducing the need for multiple "handovers" of a spacecraft during an orbit and the subsequent reestablishment of the

communications links. This continuous coverage by a selected number of resources reduces the costs associated with maintaining a space communications network and results in increasing the inherent reliability of the communications service through redundancy at critical points in the network.

The TDRSS satellite has two 4.9-meter diameter "single access" (SA) parabolic dishes. Each of these antennas can be pointed via the TT&C and provides both S-band and K-band links between the user satellites and the TDRS, referred to as the S-band single access (SSA) and K-band single access (KSA) services. The TDRS are nonprocessing satellites, i.e., the transponders in the TDRS are "linear bent-pipe" frequency translators. The SA signals are translated to/from their assigned link frequency and the TDRS/ground frequency and retransmitted. Only the TT&C links are modulated, demodulated, and processed in the satellite. An uplink pilot recovered in the TDRS provides the satellite the reference frequency source for these translations.

A third antenna system present on the TDRS is a 30-element array, all of which can receive, and 12 of which include diplexers to permit transmitting. The multiple access (MA) array, which is comprised of these elements, is on the surface of the TDRS facing the earth. On the TDRS, the MA forward signal is received from the ground. Phase and gain weighting is applied before the forward service signal is fed to the transmit elements to affect the beam required to focus the forward link at the intended user. These phase and gain weightings are calculated in the ground terminal based on user position and sent to the TDRS over the TT&C link.

The MA return signals are taken from the output of the antenna elements and sent to the ground terminal on 30 FDMA subcarriers. The beamforming and nulling necessary for the MA service is performed at the ground terminal by an adaptive ground implemented phase array (AGIPA). The return service ground portion is specified to provide up to 10 return services per MA subsystem, but this limitation is primarily a function of the ground terminal and not the TDRS, and therefore can be expanded to provide more services as required.

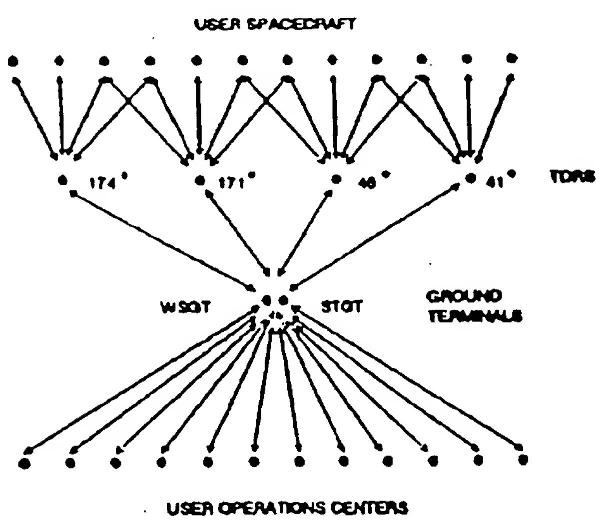

Figure 1. TDRSS Network Structure Connectivity from User Spacecraft to OCs

Chief among the waveforms employed by the TDRSS is unbalanced quadriphase shift keying (UQPSK). This QPSK waveform can accommodate the transmission of two independent data streams on the same carrier, but UQPSK permits data rates and power to be "unbalanced" between the two data sets, with the intent being equal E_b/N_0 on the two data sets at different rates for optimum efficiency and communications performance. From a satellite transponder implementation standpoint this capability permits independent data sources on a single platform or bus to use a single RF link to/from TDRS without the need for multiplexing the data channel.

More common constant envelope waveforms can be thought of as special cases of the UQPSK waveform. For example, BPSK can be seen to be infinitely unbalanced QPSK with the low rate/power channel going to zero. QPSK/SQPSK are UQPSK waveforms where, by definition, a 1:1 rate ratio is maintained, and power unbalance is usually considered a distortion in the modulation process rather than a waveform characteristic.

The return communications services are divided into data group 1 (DG-1) and data group 2 (DG-2) for spread and nonspread services, respectively. Provision for a "split" service, i.e., a signal with both spread and nonspread data, is provided in DG-1, mode 3. Each of these groups is further categorized based on whether the return service carrier (and code, if present) is coherent derived from the received forward service (Table 1) as in DG-1, modes 1 and 3. For mode 2, the return signals are derived from the oscillator on board the user spacecraft. While this induces potential frequency error of the return service due to user oscillator errors, it does result in 1/2 the unmodelled doppler offset due to user motion since the effected signal is a one-way-only service. A maximum unmodelled frequency offset of 4000 Hz is required to be acquired, though the total maximum offset from nominal IF frequency is > 2 MHz.

For all services (SSA,KSA,MA), range rate measurements (one way or two way, depending on the service) are required. Range sum measurements are also required to be made for SSA/MA DG-1, modes 1 and 3. Accurate range and doppler measurements on the links from the ground to the TDRS to the user to the TDRS to the ground, i.e., range sum and range rate sum, are crucial to the mission of the Flight Dynamics Facility (FDF) to maintain up to date satellite ephemeris information. In addition to other uses, this information is in turn used by the TDRSS ground terminals to aid in acquisition of the signals from the user spacecraft.

INTEGRATED RECEIVER DESIGN DESCRIPTION

The Integrated Receiver is part of the User Services Subsystem (USS) which provides all the user communications signal processing for the TDRSS ground terminals. The IR is the common element in the SSA, MA, and KSA services, providing all data processing for SSA and MA, and providing coverage of KSA up to 6 Msps each I and Q, even when either I or Q data rate is outside the IR data rate range. The high data rate receiver (HDRR) is required only to process KSA signals that are outside the SSA range. When both I and Q data rates are outside its range, the IR is still required to acquire and track the carrier to provide doppler tracking services and coherently demodulate the TDRS single-access antenna autotrack error signals.

How the diverse nature of the TDRSS waveform stresses the demodulator becomes evident as one examines the range of requirements for the return services. The data rates for TDRSS

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require the accommodation of a 62.3-dB dynamic range. The I and Q data channel rates can vary independently, and the portion of the total carrier power in the I and Q channels, as determined by the relative phase angles generated in the modulator, can vary up to 6 dB. As indicated in Table 1, DG-1, mode 3 includes PN spread data on I and nonspread data on Q. As an additional complication, the data waveforms can be either biphase or NRZ, encoded with either a rate 1/2 code, one of two rate 1/3 codes, or not encoded. The flexibility to mix data streams on a single carrier is one of the advantages of UQPSK and also one of its challenges. To optimumly take advantage of this flexibility, the modem(s) in the ground terminal has to be capable of demodulating one channel at the minimum symbol rate with the other channel at the maximum symbol rate, both of which can have different data formats and characteristics while achieving near-theoretical BER, cycle slip, and symbol synchronizer performance.

Figure 2 is a simplified block diagram of the IR. With the exception of the double-conversion dual-channel front end, the IR is an all-digital UQPSK demodulator with dual-carrier recovery loops that can operate in concert or independently. Dual independent symbol-timing recovery loops provide signals for clocking the A/D converters, the integrate and dump arm filters, and the decoders/deinterleavers/data output channels. This use of symbol-timing feedback is how the IR derives its name and is a primary reason the IR achieves the required performance. Independent I/Q timing recovery is required to support the special needs of UQPSK over the wide, continuous data rate and signal level ranges present. The remainder of this section describes the operation of the main sections of the IR, and how it supports the variety of modes required.

Downconversion/Sampling. The IR makes extensive use of digital signal processing to achieve its required flexibility and performance. Until the input "analog" waveforms are converted to a digital representation, they are subject to analog degradations. The conversion process is critical for the overall performance of the demodulator and required to be implemented early in the processing of the input. The 370-MHz IF input is transformed to baseband via a double conversion process using two NCO-D/A converter-filter combinations to generate the local oscillators (LO). The first LO is a "semiclosed loop" 300-MHz source which is variable to allow $\pm$1.6-MHz center frequency range about the nominal IF. This range is required to support the doppler on the K_u-band services and allow for user oscillator uncertainty. The tuning of this source is controlled by the firmware based on the expected signal frequency (acquisition) and the gross error experienced by the second LO after signal acquisition. By providing this "precorrection," the range required to be covered by the closed loop 70-MHz second LO is reduced to the unmodelled frequency errors prior to acquisition, and even less after signal acquisition.

Conversion to digital is performed at a minimum of four times the symbol rate, independently for the I and Q channels, and the signal is then finite impulse response (FIR) digitally filtered. This permits the antialiasing filters cutoff frequency to be well outside the signal bandwidth, minimizing losses due to filtering distortion. On the other hand, the FIRs set the noise bandwidth at twice the symbol rate and provide a decimation by two to the desired sample rate at the same time. The sampled data is routed to the arm filters and the PN acquisition hardware.

Carrier Recovery. The heart of any coherent demodulator is the carrier recovery scheme. For optimum QPSK performance, all of the carrier information should be used, i.e., the error data from both the I and Q channels combined. The IR uses a switchable $2^{nd}/3^{rd}$ order carrier tracking loop, with an FFT to aid in acquisition, to accommodate the high dynamics associated with spacecraft during maneuvers at low C/N_0. The carrier loop is a hybrid implementation, with the NCO output D/A converted and filtered, and analog mixing used at the second IF. The baseband

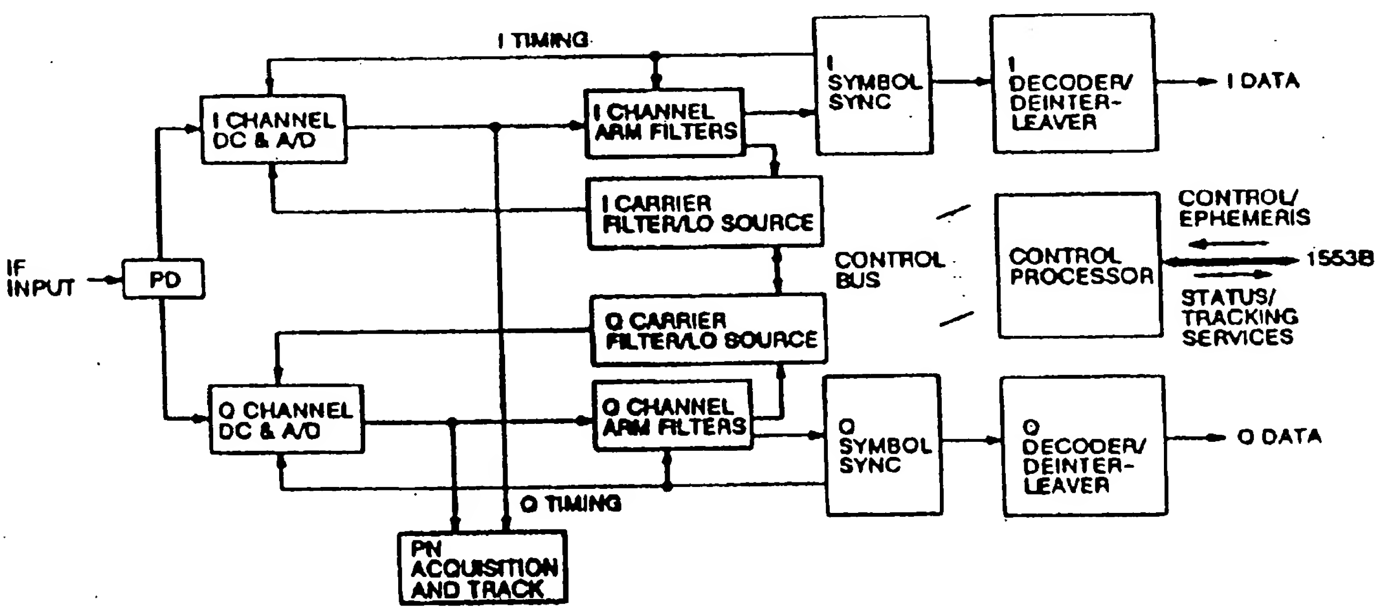

Figure 2. IR Top Level Block Diagram

data is then converted to digital for the remainder of the processing. This structure applies to the IR architecture as a whole.

For UQPSK waveforms, the combining of both I and Q carrier errors has been examined [1] for active arm filters and a weighting for the contribution of each arm recommended, which optimized the error performance in a maximum a priori (MAP) sense. An analysis of the additional error due to "crosstalk" between the low- and high-rate data and carrier error signals was also presented. For balanced QPSK, the crosstalk terms are equal (both magnitude and rate) in the I and Q channels and cancel when the error signals are combined. To achieve the equivalent cancellation for UQPSK, the same conditions are created in the IR through the inclusion of a second set of I/Ds to "rate match" the two channel's error signals. The arm scaling gains are selected to cause the crosstalk terms to be equal after the additional I/D, thereby eliminating the crosstalk. This gain selection results in an effective scaling into the combiner of $1/\sqrt{K}$, where K is the power ratio between the channels. This weighting correlates well with the recommended MAP gains, and results in squaring losses far less than that previously achieved.

PN Acquisition/Processing. One of the driving requirements for the Integrated Receiver comes from the frequent reassignment of ground terminal resources from one spacecraft to the next and the need to be able to maximize the effective utilization of the terminal. Though the ground terminal receives user ephemeris information from the FDF and uses it to "steer" the loops prior to acquisition, a considerable range of unknown offset still exists in doppler and code state (4000 Hz and 4400 chips). The IR is required to acquire PN and carrier at 36 dB-Hz in less than 1 second with P_a > 0.9, and P_{fd} < 0.01. To accomplish this, the IR uses a PN acquisition scheme [2] comprised of a parallel code state search and a hybrid (peak detect and threshold) detection approach. The two independent code generators are used to permit the search of one code uncertainty range while the previous range's peak is compared to a threshold in a narrowed bandwidth to prevent false acquisition detection.

Symbol Timing/Data Processing. The IR uses a digitally implemented data-directed delay lock loop for symbol timing recovery. The arm filters run over the period from 3T/4 to T/4 (NRZ and biphase) and T/4 to 3T/4 (biphase only) and the outputs combined to form the symbol estimates and timing error signals. Transition presence is used to enable the timing error to update the loop filter, which in turn provides a new control word to the NCOs. The NCOs run at a minimum of four times the symbol rate to provide the sampling clocks for the A/D conversion process and are divided down and selected to provide timing to the I/Ds and clock symbols into the decoders and/or out of the IR. The symbol syncs generate independent timing for the A/Ds, I/Ds, etc., permitting the I and Q signal processing channels to be optimized to the symbol rate they are processing.

After symbol timing is recovered, if the symbols are encoded, the soft decisions are decoded by either rate 1/2 or rate 1/3 decoders, as applicable. For MA and SSA, the symbols are first deinterleaved using a (30,116) convolutional deinterleaver included in the unit.

Tracking Services. The original TDRSS ground terminal performed tracking services external from the data modems using a combination of frequency multipliers and counters and time interval counters. The forward service, which ideally would follow a frequency profile to match the user motion and thereby minimize the frequency error seen at the user, would be clamped to a known fixed frequency to provide a nonvarying doppler reference. The epochs out of the forward code generator and return replica generator provided the "start" and "stop" for the measurement of the time delay from the ground to the user and back to the ground. These epochs would be switched to pair the active forward and return service equipments and the recovered carrier from the active receiver LO providing the return doppler indication.

All of the above functions are performed internal to the IR, in conjunction with its matching modulator, by using the basic information that is already contained in the firmware in the processors that control the units. Both the IR and matching modulator take advantage of direct synthesis NCOs being digital devices, the output of which at any time is known given that the initial state, the history of the input controls, and the timing relations between the reference clock and control word update clock are known.

Both the modulator and IR use the user ephemeris information in the processing of tracking services. The modulator uses it to generate the frequency profile to match the doppler the user will have when the signal arrives at the user to minimize stress on the transponder. The IR uses the ephemeris to steer its acquisition window about where it expects the signal when it returns from the user and to provide knowledge of the forward frequency and code state.

After the user satellite transponder acquires the forward signal, the return signal frequency reflects the two-way doppler information and forward frequency profile, and the return PN code reflects the time delay relative to the forward transmitted code. Since the IR has the same information the modulator used to generate the NCO control words for the forward service, the IR can calculate the forward signal history and therefore the current state, without any direct connection with the modulator. Likewise, the IR knows the sequence of control words it generated in response to loop errors to control the carrier and code tracking loops, and therefore it has the doppler and code state information for the return signals. Using this information, which is already present as part of the demodulator implementation, the IR performs the tracking services without the need for additional equipment or direct connection between the forward and return equipments. Inhibiting the doppler compensation on the forward service is not necessary since, with the full knowledge of the forward signal, the IR can compensate for the changing modulator output. This eliminates the "stress" in the user transponder caused by a widely varying input signal (and therefore one source of potential communication service interruption) since loss of forward signal lock can cause interruption of return signal transmission.

IMPLEMENTATION

The Integrated Receiver is packaged as a single 12.25-inch-high rack- mounted chassis. High-speed CMOS (HCMOS) is the prevalent circuit technology, with some ECL present in the downconversion/digitization processes. Communications devices from several manufacturers are extensively employed, including PN matched filters, PSK demodulators, FIR filter, decoder, DSP and NCO chips. This level of high-gate count application specific integrated circuits (ASICs) and custom devices permit the entire design to be contained on 14 VME size boards, including a commercially available MC68030 processor board with RAM, program memory, and bus management.

The heart of the demodulator is a four-board set consisting of two demod/symbol sync boards, an output processor, and a demod

processor. Each demod/symbol sync board includes a BPSK demodulator (minus the loop filter), two 2 bit x 1024 tap acquisition correlators, a symbol delay lock loop, FIR, and the carrier loop NCO-D/A-filter. The output processor has the decoding and deinterleaving functions, as well as I/Q and external input postdetect combiners. The demod processor implements the carrier loop, and such functions as symbol sync and decoder control, ambiguity resolution, and acquisition and lock detection. The unit receives mode control, configuration, and ephemeris data from the control computers via a MIL-STD-1553B bus and provides unit status and configuration, BIT/BITB information, and tracking services measurements by the same path. A 12-line by 40-character LCD display/touchpanel is provided to permit operation and display of status and information by a local operator.

The critical limiters on IR data rate are the operating speed of the digitization, matched filtering, and digital signal generation (NCO) devices. The IR employs both 1.5- and 1-micron CMOS technology for the demodulator and acquisition correlator ASICs, which in many cases are intrinsically capable of exceeding the speeds required. The costs associated with ASIC and custom devices are going down while the tools to develop these devices are becoming more plentiful and powerful, further increasing their attractiveness. A/D conversion devices, NCOs, etc., of higher speeds then required for the STGT are available today with the future sure to hold faster and more capable devices. Parallel architecture approaches are being used to permit multiple lower rate data paths to handle higher rate processing tasks. Lastly, processes which have been implemented in firmware can be moved to dedicated hardware as the need to process high rates is felt. On the whole, extension of this architecture to higher data rates is very practical and is being investigated at this time.

SUMMARY

The TDRSS provides a flexible communications system for low-earth orbit spacecraft and a source of tracking data to permit the location of the many orbital platforms to be accessed. As such, TDRSS and its successors will provide the basis for near-earth and potentially deep-space communications for the foreseeable future. Central to the TDRSS ground terminal is the Integrated Receiver which provides data demodulation, decoding, and deinterleaving over the range of 100 sps to 12 Msps, and all the tracking services in a single high-performance design. This approach — using a single digital architecture to provide the adaptability without the penalty suffered by analog implementations forced to operate over continuous ranges — has proven to be very successful. Digital technologies and devices have now advanced in functional capability, speed, and level of integration such that a greater range of data rates and formats are applicable. As such, they hold promise for higher and higher rates of space data communications systems in the future at increasingly lower acquisition and operating costs.

REFERENCES

1. W. K. Simon, "Two Channel Costas Loop Tracking Performance for UQPSK Signals with Arbitrary Data Formats," IEEE Transactions on Communications, Vol. COM-26, No. 9, Sept 1981, pp 1275-1289.

2. J. R. Luecke, "Comparison of Detection Schemes for Fast Acquisition Direct-Sequence Spread-Spectrum Receivers," Conference Proceedings at the 1989 IEEE Military Communications Conference (MILCOM 89), 15-18 October 1989, Boston MA.